The LHC Collimation System

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circumference: 26.7 km

The LHC Collimation System – Contents

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- Beam Loss

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- Collimators and Machine Protection
- Requirements of the Collimators

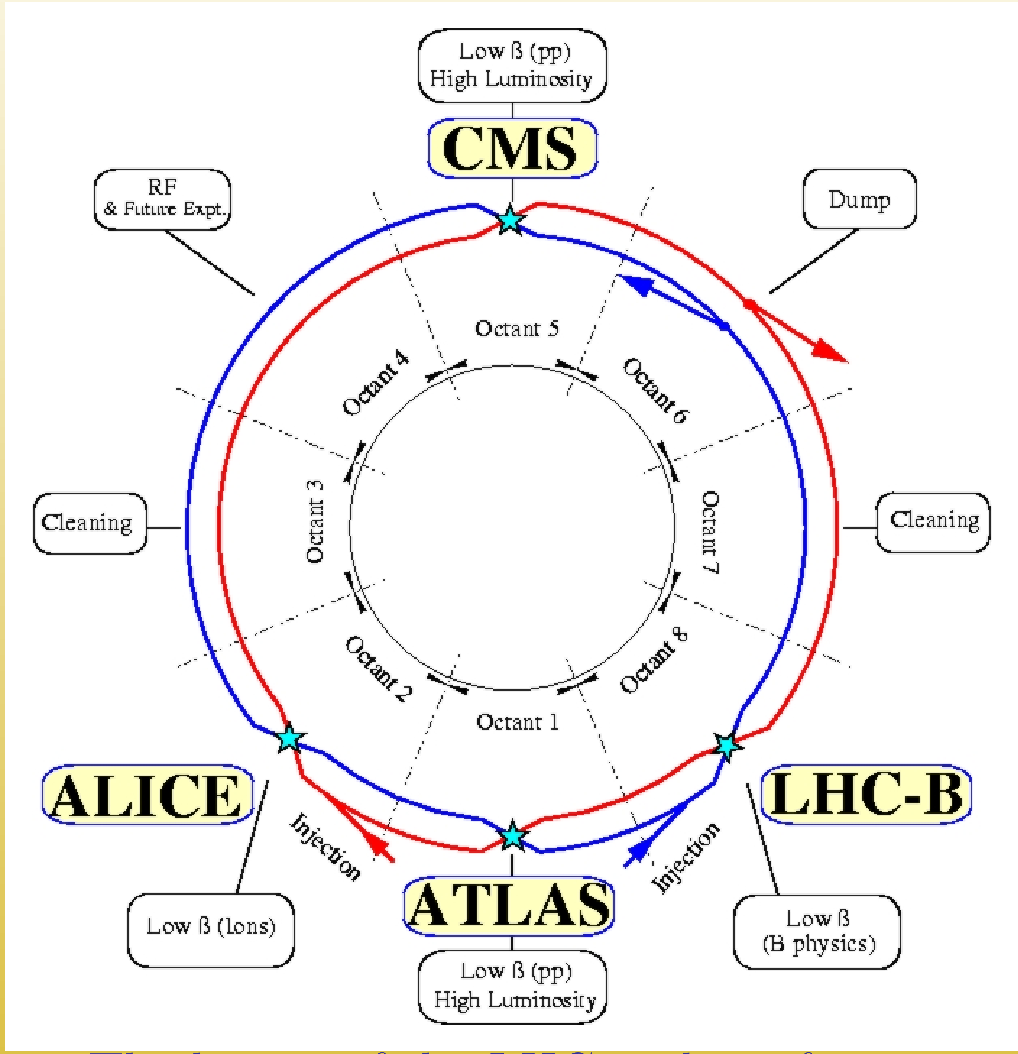
The Large Hadron Collider at CERN

p-p collisions

- center of mass energy: 14 TeV
- luminosity: $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

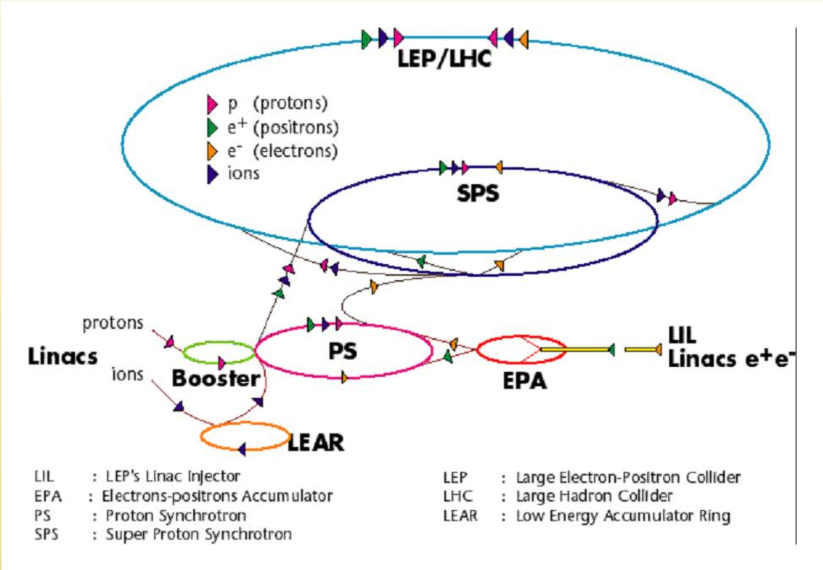
heavy ion collisions (Pb-Pb)

- center of mass energy: 1150 TeV
- luminosity: $10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



The layout of the LHC with its four experiments

p-p Collision Mode



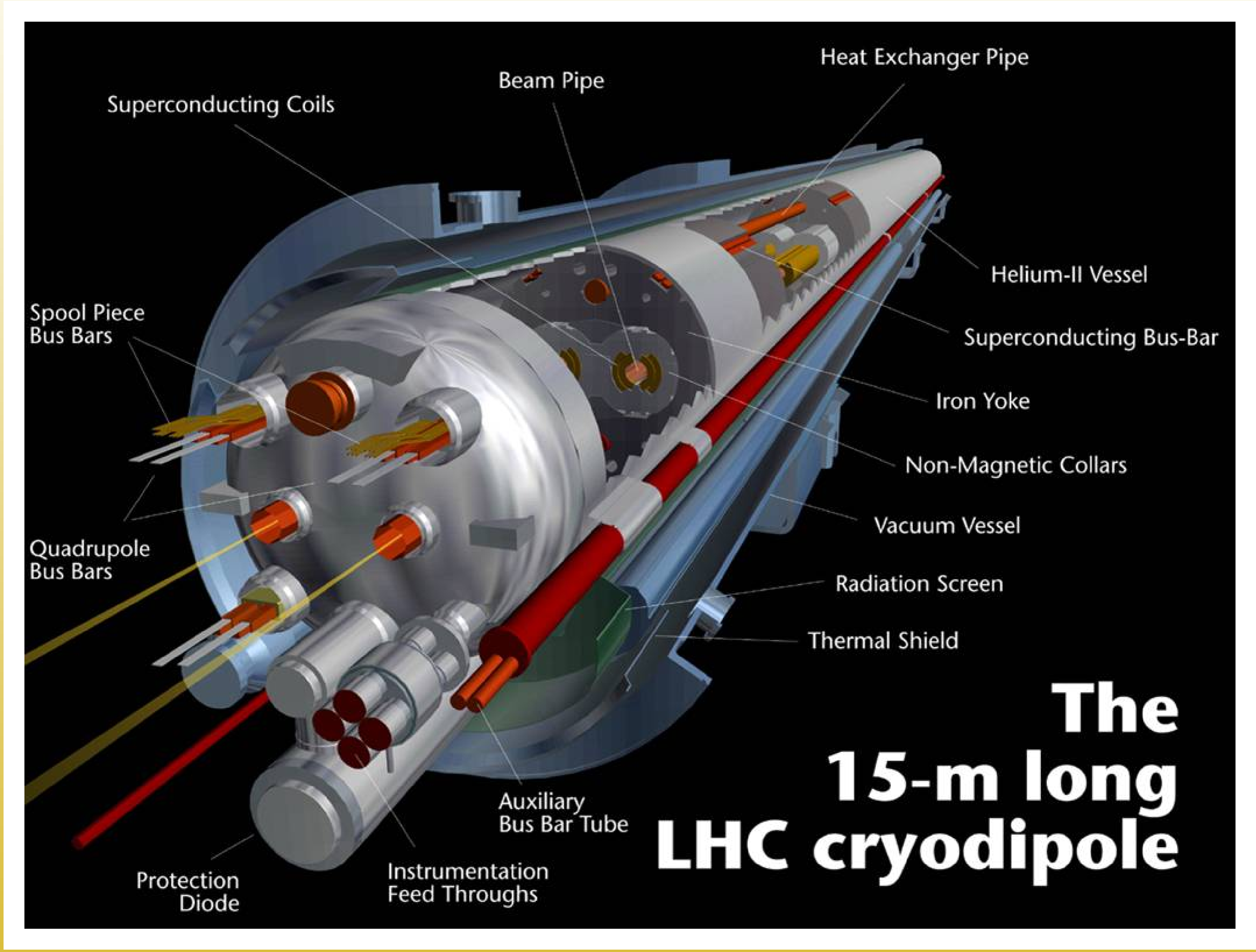
The injector chain

momentum	7 TeV/c
number of bunches	2835
particles per bunch	10^{11}
bunch spacing	25 ns
frequency	11 kHz
energy stored per beam	$\sim$ 350 MJ

Magnetic guide field for 7 TeV protons: **8.3 T**
$\Rightarrow$ **superconducting** magnets cooled in **superfluid He (1.9 K)**

The 15 m long dipole magnets provide bending of $\phi = 5.1\text{mrad}$
$\frac{2\pi}{5.1\cdot 10^{-3}} \rightarrow 1232$ main dipole magnets

Two-in-one Dipole Magnets



Parameters pushed to the extreme ⇒ new scale of complexity

Demanding Issue:
Safe Operation of LHC

Energy loss per turn/proton/7 TeV	6.7	keV
Radiated power per beam/7 TeV	3.8	kW
Stored energy per beam/7 TeV	350	MJ
Stored energy in magnets/7 TeV	11	GJ

- Proton energy **a factor 7 above other machines**
- energy stored in the beams more than **a factor 100 higher**
  - ▷ **Machine Protection System** is a vital part of the machine
- beam must be handled in **superconducting area**
- sudden loss of $\sim 10^6$ protons at 7 TeV: **quenches**
- Quenches, powering failures, …could cause the beam to be lost.

▷ The energy stored in the beams is sufficient to heat 500 kg copper from 1.9 K to the melting point.

Collimators are a machine protection tool.

Beam Losses in the LHC

Continuous beam loss

- under normal conditions
  due to
  - imperfections of the machine
  - nuclear interactions, beam-gas collisions

Irregular beam loss

- failures of equipment
- operation errors

Continuous Beam Loss

Halo particles are lost at aperture restrictions.

Processes for creation and regeneration of the halo:

- p-p collisions at the IP
  - elastic, inelastic, single diffractive

- beam-gas
  - Rutherford scattering
  - multiple Coulomb scattering
  - elastic nuclear scattering
  - inelastic nuclear scattering
- intra-beam scattering
  - Touschek effect
- Resonance crossing
  - beam-beam effect, space charge

Loss rate

	Injection [p/s]	Collision [p/s]
Beam-gas		
Nuclear elastic	$7.64 \cdot 10^7$	$1.74 \cdot 10^6$
Nuclear inelastic	$2.08 \cdot 10^8$	
Multiple Coulomb	$1.43 \cdot 10^8$	$3.30 \cdot 10^6$
Intra-beam scattering		
Transverse	$3.71 \cdot 10^7$	$7.18 \cdot 10^6$
Longitudinal	$4.85 \cdot 10^8$	$1.30 \cdot 10^8$
Touschek	$6.03 \cdot 10^6$	$5.03 \cdot 10^6$
Resonance crossing		
Beam-beam		$3.76 \cdot 10^9$
Total	$9.55 \cdot 10^8$	$4.11 \cdot 10^9$

Estimation for LHC: Total loss outside of insertions:

$\dot{\mathrm{N}}_{\mathrm{p,inj}} \sim 7.4 \cdot 10^8\,\mathrm{p/s} \quad \dot{\mathrm{N}}_{\mathrm{p,coll}} \sim 3.91 \cdot 10^9\,\mathrm{p/s}$

Quench level at top energy: $\dot{\mathrm{N}}_{\mathrm{q}} = 7.6 \cdot 10^6\,\mathrm{p/m/s}$

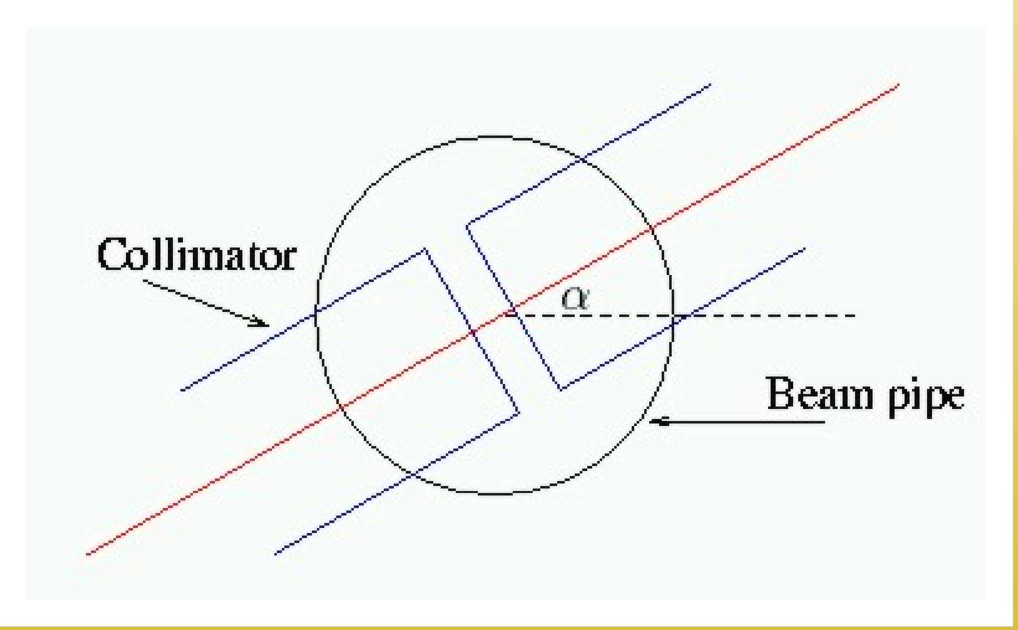
LHC needs collimation throughout the whole cycle of operation

in order to:

- ▷ minimize background in the experiments
- ▷ limit irradiation of equipment close to the beam
- ▷ **avoid quenching magnets**

LHC collimators:

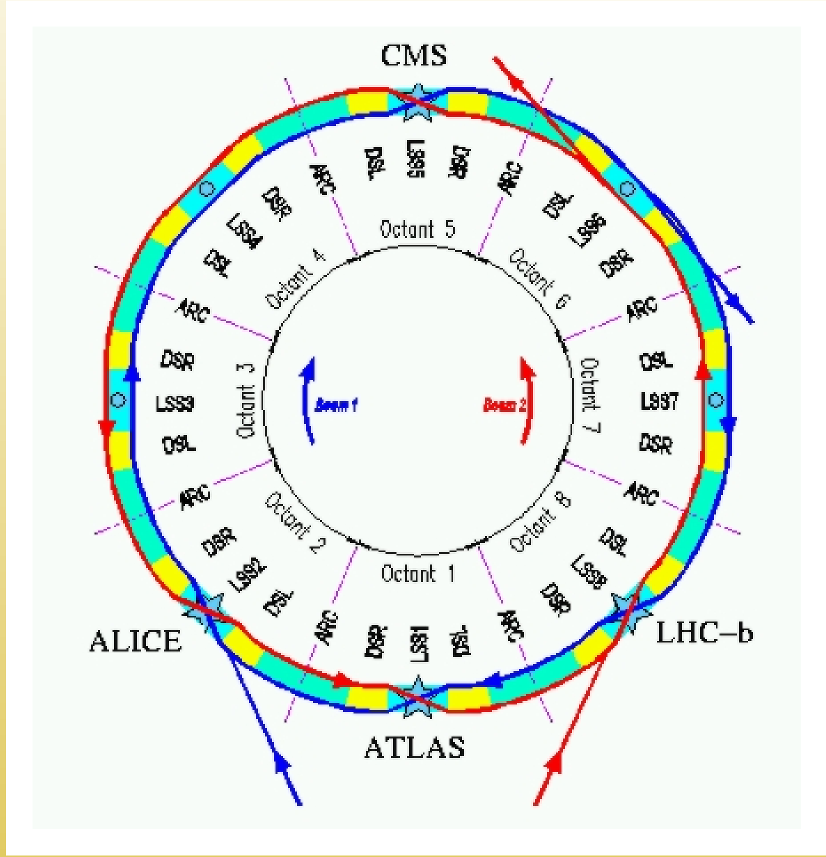
- blocks of materials
- 2 radially movable jaws
- installed on opposite sides of the beam



Two insertions for beam cleaning

Momentum cleaning and betatron cleaning installed in different insertions.

- betatron cleaning: **IR7**
- momentum cleaning: **IR3**, large $D_x/\sqrt{\beta_x}$



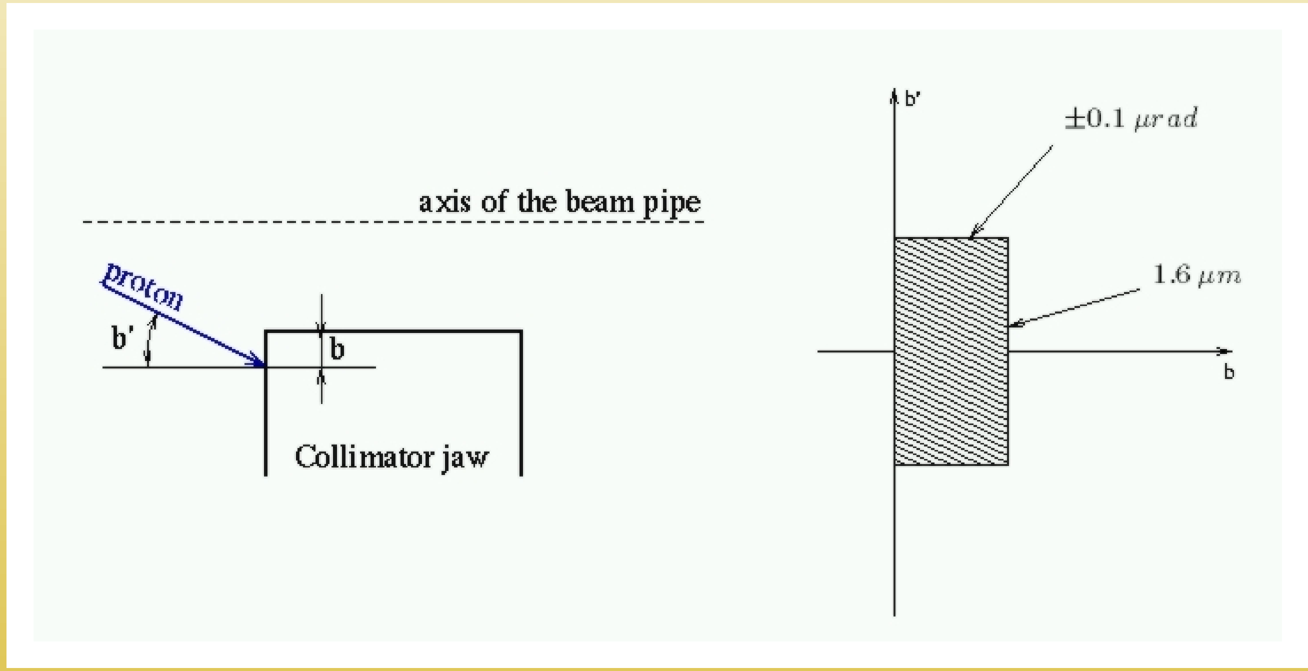
A fraction of 10^{-7}-10^{-9} of beam sufficient to quench ⇒ strict requirements on collimators:

- define aperture limit in the ring: amplitudes under 10σ
- continuous loss to be suppressed better than 99.9%

Two-stage Collimation System

small impact parameters at collimators

- 50%-probability for out-scattered protons
- additional collimators downstream to capture out-scattered protons



$\Rightarrow$ **Primary** and **secondary** collimators

Optics of a two-stage collimation system

If D(s) has its peak at the primary collimator

- ▷ same considerations for momentum and betaron cleaning
- ▷ momentum cleaning reduced to betatron cleaning (in one plane) if $\frac{1}{\mathrm{D}}\frac{\mathrm{dD}}{\mathrm{ds}} = -\frac{\alpha}{\beta}$

Betatron Cleaning

- relative aperture between primary (n_0) and secondary collimator (n_1)
  - normalized aperture $\mathrm{n}_1 > \mathrm{n}_0$
  - difference n_0-n_1
    - amplitude smearing: estimation: 0.5σ
    - orbit changes during operation: estimation: 0.5σ

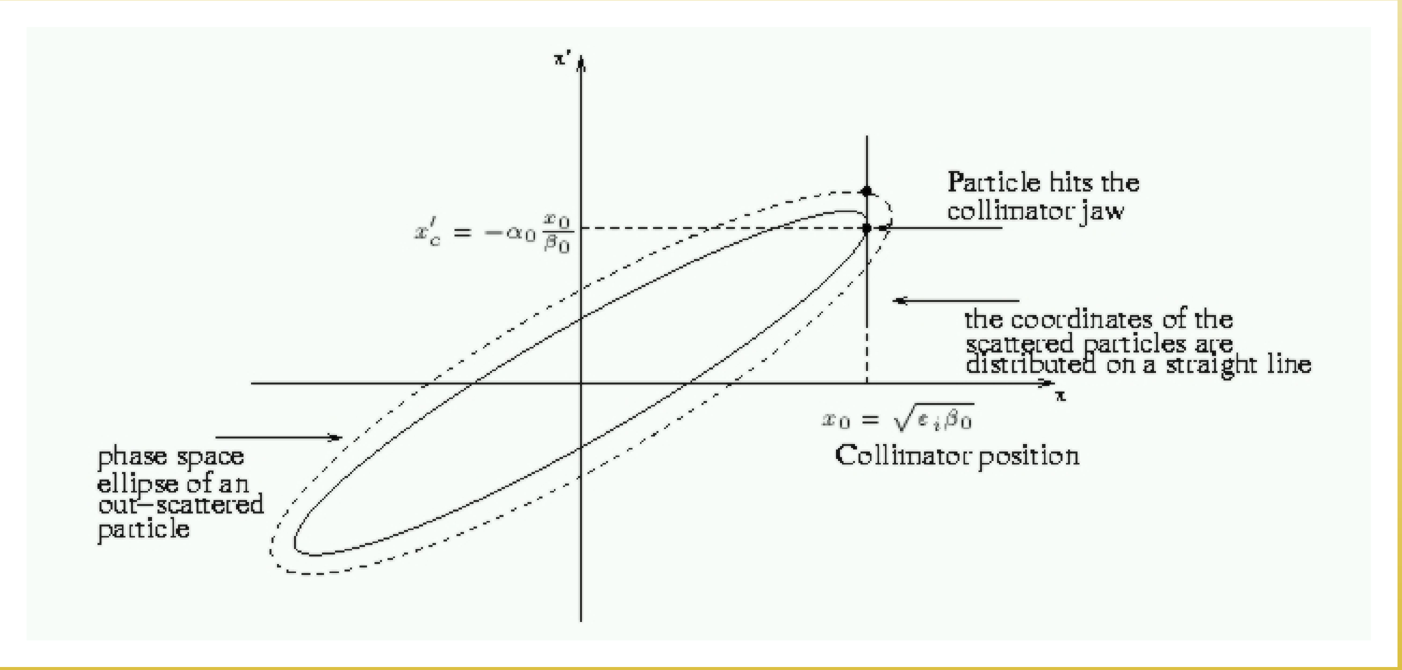
    $\Rightarrow \Delta\mathrm{n} = \mathrm{n}_1 - \mathrm{n}_0 = 1$
  - LHC: $\mathrm{n}_0 = 6$, $\mathrm{n}_1 = 7$
- relative longitudinal position (phase advance)

Optimum Phase Advance for Secondary Collimation

assuming horizontal collimation

- impact parameters are small $\Rightarrow x_0 = \sqrt{\varepsilon_i \beta_0(s)}$, $x'_0 = -\frac{\alpha_0}{\beta_0} x_0$, $\varepsilon_i = \frac{x_0^2}{\beta_0}$
- Scattering in the collimator jaw: proton might be scattered into the vertical plane. **Plane** and **orthogonal** scattering.

Plane Scattering



Plane Scattering

- scattering angle Θ is added to initial angle $\mathbf{x}'_0$
- increase of ε_i:

$$\varepsilon_i^* = \varepsilon_i + \beta_0 \cdot \Theta^2$$

- betatron phase jump $\delta\phi$:

$$\delta\phi = \pm\mathrm{arcos}\sqrt{\frac{\varepsilon_i}{\varepsilon_i^*}} = \pm\mathrm{arcsin}\sqrt{\frac{\varepsilon_i^* - \varepsilon_i}{\varepsilon_i^*}}$$

- ansatz for horizontal displacement at secondary collimator:

$$\pm x_1 = \sqrt{\varepsilon_i^* \beta_1}\cos(\delta\phi + \Delta\phi)$$

- $\Rightarrow$ equation relating Θ and $\Delta\phi$:

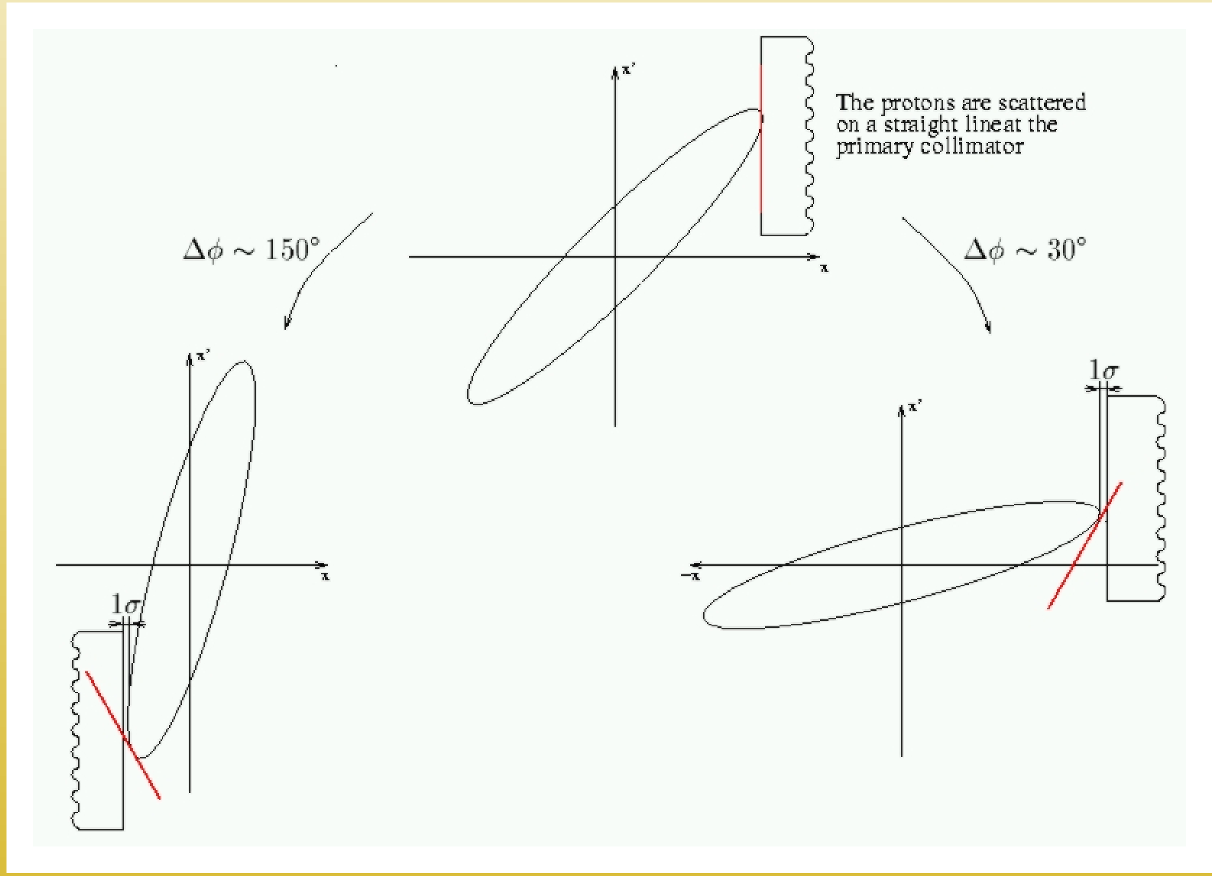
$$\Theta = \frac{\frac{x_0}{\sqrt{\beta_0}}\cos\Delta\phi \mp \frac{x_1}{\sqrt{\beta_1}}}{\sqrt{\beta_0}\sin\Delta\phi}$$

- minimum for Θ for phase advances:

$$\Delta\phi = m \cdot \pi \pm \text{arcos}\left(\frac{n_0}{n_1}\right)$$

- LHC: $n_0 = 6$ and $n_1 = 7$:

$$\Delta\phi \sim m \cdot 180^\circ \pm \sim 30^\circ$$



Orthogonal + Plane Scattering

- 2D-ansatz for derivation of optimum phase advance
- number of secondary collimators per primary collimator: 4
- result contains
    - optimum phase advance
    - tilt angle of the jaw of secondary collimator

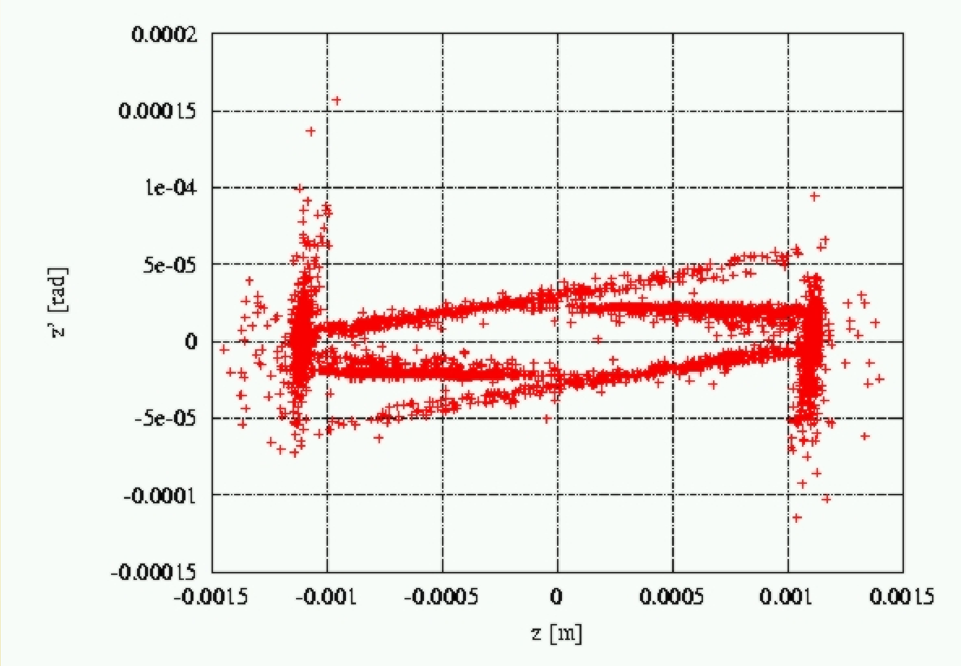
LHC:

- IR7: 4 primary collimators, 16 secondary collimators
- IR3: 1 primary collimator, 6 secondary collimators

Proposal so far for the materials and length of the collimators:

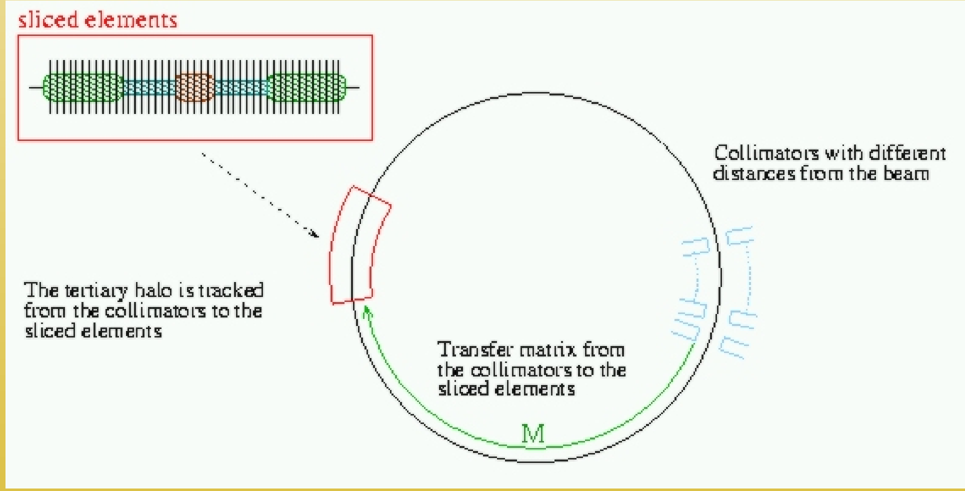
- primary: aluminum, 20 cm
- secondary: copper, 50 cm

Tertiary Halo



Vertical tertiary halo.

- Distribution highly nonuniform
- MC Picker provided for beam instrumentation and experiments
- Slicetrack



Slicetrack

- Calculates longitudinal loss maps along LHC elements.

Collimators & Absorbers at 7 TeV

Region	Type	Orientation	Material	Number	Length	Setting
IR1	TCL (Q5)	X	Cu	2	1 m	10σ
	TAS	Round	Cu?	2	1.8 m	12σ
	TCL (D2)	X	Cu	2	1 m	10σ
IR3	TCP	X	Al	1	0.2 m	8σ
	TCS	X,Y,XY	Cu	6	0.5 m	9.3σ
IR5	TCL (Q5)	X	Cu	2	1 m	10σ
	TAS	Round	Cu?	2	1.8 m	12σ
	TCL (D2)	X	Cu	2	1 m	10σ
IR6	TCDQ	X (1side)	C	1	9.5m	10σ
IR7	TCP	X	Al	1	0.2 m	6σ
	TCS	X,Y,XY	Cu	6	0.5 m	7σ

Settings for nominal luminosity and nominal β^*.

BUT . . .

Beam Lifetime	Beam Power Deposit per Beam	Scenario, Comment	Operation	Dump
100 h	1 kW	good condition	YES	no
10 h	10 kW	collimation system is necessary	yes	no
1 h	100 kW	with efficient collimators	short time	not urgent
1 min	6 MW	equipment or operation failure	no	yes
1 s		equipment failure	NO	fast
15 turns $\sim$ 1.3 ms		failure of D1 magnet	NO	very fast
1 turn $\sim$ 0.1 ms		failure at injection, failure of beam dump kicker or injection kicker; protection only by collimators	NO	no more possible

Requirements on Minimum Beam Lifetime

Normal Operation

Mode	Energy [TeV]	Duration [s]	required min. lifetime [h]	Beam deposition [protons/s]	Power deposition [kW]
Injection	0.45	cont	1.0	$0.8 \cdot 10^{11}$	6
		10	0.1	$8.2 \cdot 10^{11}$	60
Ramp	0.45-7	10	0.1-0.2	$8.2 - 4.1 \cdot 10^{11}$	60-465
	0.45	~ 1	0.006	$1.3 \cdot 10^{13}$	1000
Top energy	7	cont	1	$0.8 \cdot 10^{11}$	93
		10	0.2	$4.1 \cdot 10^{11}$	465

Irregular Beam Loss

- BLMs near collimators trigger beam dump
- 2-3 turns necessary to dump the beam

Requirements on Minimum Beam Lifetime

Critical One-turn Failures

Failure mode	Beam energy [TeV]	Intensity deposit [protons]	Energy deposit [kJ]	Transverse dimensions [mm×mm]	Impact duration [ns]
Injection oscillation	0.45	$2.6 \cdot 10^{13}$	1875	1.0×1.0	6250
Asynchronous beam dump (all modules)	0.45 7	$1.1 \cdot 10^{12}$ $2.8 \cdot 10^{11}$	78 311	**5.0**×1.0 **1.0**×0.2	275 75
Asynchronous beam dump (1 out of 15 modules)	0.45 7	$1.1 \cdot 10^{12}$ $6 \cdot 10^{11}$	78 667	**5.0**×1.0 **1.0**×0.2	275 150

Do the so far chosen materials meet the requirements??

Summary of Requirements for LHC collimators

- Survival of jaws with 7 TeV proton impact (no melting, cracks, dust formation,...)
  - $\mathbf{2 \cdot 10^{12}}$ p (2.2 MJ) in 0.5 μs over area of 1 mm(full width)x 0.2 mm(rms)
  - $\mathbf{4 \cdot 10^{12}}$ p (4.5 MJ) in 10 s over area of 0.03 mm(rms)x0.2 mm(rms)
- Excellent cleaning inefficiency
  - Local losses $\sim \mathbf{10^{-5}}$ of primary beam halo
  - Deformations of $\sim \mathbf{1.0}$ m long jaws $< 25\ \mu$m
  - Control/maintain beam-jaw position/angle ~ 0.1 mm, $\sim 60\ \mu$rad

AND: Collimation must be available from day 1 of LHC operation

Material Damage with LHC Beams

Destruction Limits

	Destruction Limit [nominal intensity]	
	450 GeV	7 TeV
Copper	1.9e-3	1.8e-5
Beamscreen	1.6e-3	7.0e-5
S.C. coil	4.2e-3	14.0e-5

This made the reconsideration of the present collimator material necessary.

Two possibilities:

- Solution with efficient robustness that frequent damage is avoided (low Z material)
- Regular damage of the jaws. Diagnostics + remote repair/exchange possibilities of the highly radioactive jaws.

We are now investigating low Z materials. Carbon??

Carbon as Material for Secondary Collimators?

- Low Z jaws are less activated
- Remote handling requirements are more relaxed.
- But: secondary collimators would have to be longer to restore cleaning efficiency of the old system (0.5 m $\rightarrow$ 1 m)
- Space in the insertion is available and optics can be re-matched
- Vacuum group does not rule out carbon.
- Main problem at 7 TeV: C system increases impedance tenfold
- Open question: e-cloud
- Other solutions:
  - Low Z system based on Beryllium
  - Tertiary collimators at triplets
  - Short high Z jaws with easy diagnostics and repair/exchange

Schedule

Sep 2001	LHC Beam Cleaning Study Group
Jan 2002	Consensus to consider low Z-material
Jun 2002	Consensus on detailed requirements
Oct 2002	Project LHC Collimation new group First tolerances
Jan 2003	Full simulation chain: Beam – FLUKA – ANSYS Cleaning efficiency and optics with low Z Review of Impedance, other constraints
April 2004	Prototype Collimator
2004/2005	Production
2006	Installation